(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number : 0 657 754 A1

(12) EUROPEAN PATENT APPLICATION

(21) Application number : 94308073.9

(22) Date of filing : 02.11.94

(51) Int. Cl.^{6} : G02B 6/293, G02B 6/28, H04B 10/18

(30) Priority : 15.11.93 US 152655

(43) Date of publication of application : 14.06.95 Bulletin 95/24

(84) Designated Contracting States : DE FR GB IT

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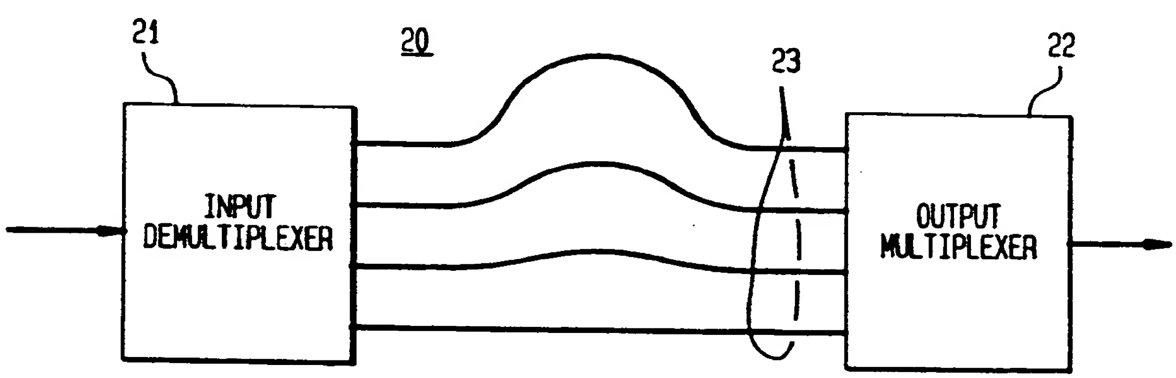
(54) Optical dispersion compensator.

(57) Pulse broadening in an optical transmission system due to wavelength dispersion is reduced by separating the different wavelength components (21,22) and selectively delaying them (23). Upon recombination, the original phases of the wavelength components are restored, and the pulses narrowed.

FIG. 2



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TECHNICAL FIELD

This invention relates to optical transmission systems and, in particular, to arrangements for reducing the effect of group-velocity dispersion in optical fibers.

BACKGROUND OF THE INVENTION

When optical waves of different wavelengths propagate along an optical fiber, they do so at different group velocities. This so-called chromatic, or group-velocity dispersion causes pulse broadening which limits the rate at which information can be carried through an optical fiber. Recently, there has been interest in dispersion compensators that use dual-mode fibers operated in the LP_{11} spatial mode, close to their cutoff wavelength. Because higher-order spatial modes in optical fibers exhibit large, negative chromatic dispersion, such an arrangement provides a means for compensating for the positive dispersion in conventional single-mode fiber spans. See, for example, U.S. patent 5,185,827, issued February 9, 1993, and assigned to applicant's assignee.

The attractiveness of using a dual-mode fiber for dispersion compensation stems from the ability to achieve large negative waveguide dispersion by operating close to the cutoff wavelength of the LP_{11} mode, thereby minimizing the amount of fiber required to compensate a given amount of positive dispersion. While the use of less fiber reduces losses, operation close to cutoff greatly increases sensitivity to bending losses, and it is these losses that place a practical limit on how much dispersion compensation can be realized.

An alternative approach to this problem is the use of dispersion shifted fibers, as described in the article by V.A. Bhagavatula et al., entitled "Segmented Core Single-Mode Fibers with Low Loss and Low Dispersion," published in Electron Lett. 19, 317 (1983). However, such fibers tend to be much lossy than one would like.

It is, accordingly, an object of the present invention to effect low loss dispersion compensation without the use of long lengths of optical fibers or specially designed fibers. It is a further object of the invention to effect such compensation by means that are not sensitive to spatial mode orientation.

SUMMARY OF THE INVENTION

When an optical pulse propagates along an optical fiber, the different wavelength components making up the pulse propagate with different group velocities. This results in a change in the relative phases of these components and the resulting broadening of the pulse. In accordance with the present invention, these phases are restored and the pulse narrowed by separating the different wavelength components and selectively delaying them.

It is an advantage of the present invention that all the components needed to produce wavelength separation, delay and recombination can be achieved by substantially lossless means. It is a further advantage of the invention that the entire dispersion compensator can be fabricated using integrated optical techniques.

These and other objects and advantages, the nature of the present invention, and its various features will appear more fully upon consideration of the various illustrative embodiments now to be described in detail in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows an illustrative optical fiber communication system to which the invention relates;

FIG. 2 shows, in block diagram, a dispersion compensator in accordance with the teachings of the present invention;

FIG. 3 shows the wavelength distribution of a typical optical pulse;

FIG. 4 shows the wavelength distribution of the input and output signals associated with the input demultiplexer;

FIG. 5 shows the differential delay lines and the delays associated with the different wavelength signal components;

FIG. 6 shows a multiplexer/demultiplexer comprising two star couplers connected by means of a plurality of differential delay lines;

FIG. 7 shows a dispersion compensator, in accordance with the invention, using multiplexer/demultiplexers employing reflective focusing diffraction gratings; and

FIG. 8 shows a dispersion compensator using bandpass filters to achieve wavelength separation.

DETAILED DESCRIPTION

Referring to the drawings, FIG. 1 shows an illustrative optical fiber communication system 10 to which the invention relates. Typically, such a system includes an optical transmitter 11 whose output comprises a series of optical pulses 15, an optical receiver 12, and an interconnecting optical fiber link 13. However, because the velocity with which optical wave energy propagates along a fiber varies as a function of wavelength, all optical fibers, both single-mode and multi-mode, introduce dispersion, which results in a broadening of the optical pulses as they propagate along the fiber. Because this broadening reduces the information carrying capacity of the system, various techniques for reducing the effects of wavelength dispersion have been proposed. Accordingly,

a dispersion compensator 14 is typically included at the output end of the fiber link 13 where the broadened pulses 16 are restored to their original shape 17. In effect, the dispersion compensator introduces a negative dispersion, expressed in the common units of picoseconds per nanometer per kilometer, that compensates for the dispersion produced in the fiber link.

FIG. 2, now to be considered, shows, in block diagram, a dispersion compensator 20 in accordance with the teachings of the present invention. The compensator comprises an input demultiplexer 21 and an output multiplexer 22 connected by means of a plurality of differential delay lines 23.

The operation of the compensator is based upon the recognition that the optical pulses have a wavelength distribution $\Delta\lambda_n$ that can be divided into a plurality of subbands of width $\Delta\lambda$, centered about wavelengths λ_1, λ_2 ... λ_i, as illustrated in FIG. 3. Because the propagation velocities of the different wavelength components are different, the phase relationships among the various components are disturbed, resulting in the undesired pulse broadening. In order to restore the correct phase relationships among the wavelengths components, in accordance with the invention, the components are separated by the demultiplexer and compensatory delays introduced. Thus, the first step in the compensation process is to separate the several different wavelength components. This is illustrated in FIG. 4, which shows the input demultiplexer 21 to which all of the wavelength components λ_1, λ_2 ... λ_i are applied, and whose output comprises the separated, individual wavelength components.

Because the shorter wavelength components tend to propagate at higher velocities than the longer wavelength components, compensation requires that they be delayed more than the longer wavelength components. Accordingly, the delays in the differential delay lines are adjusted as a function of the component wavelength. For example, in FIG. 5 the length ℓ_i of the delay line 23-i for the longest wavelength signal λ_i is less than that of all the other delay lines inasmuch as it propagates at the slowest velocity. The length of the delay line for the shortest wavelength signal λ_1 is the longest, being equal to ℓ_i plus some differential length $\Delta\ell_i$. For all the intermediate wavelength signals, $\lambda_2, \lambda_3, \ldots$, the lengths of the delay lines 23-2, 23-3...are $\ell_1 + \Delta\ell_2$, $\ell_1 + \Delta\ell_3$ ... respectively, where $\Delta\ell_1 > \Delta\ell_2 > \Delta\ell_3 \ldots > \Delta\ell_i$.

Having re-established the proper phase relationships among the several wavelengths, the compensated signals are recombined in the output multiplexer 21.

As an example, let us consider a transmission fiber of length L over which a signal of bandwidth B is being transmitted. For a fiber dispersion g ps/nm/km, the total time spread ΔT of the received signal due to dispersion is given by

$$\Delta T = BgL. \quad (1)$$

For

$$g = 15 \text{ ps/nm/km}$$
$$B = 10 \text{ Ghz} \cong 0.07 \text{ nm}$$

and

$$L = 100 \text{ km},$$
$$\Delta T = 100 \text{ ps}.$$

The increased length ℓ of the resulting pulse traveling through the fiber is

$$\ell = c/n\Delta T \quad (2)$$

where c is the velocity of light and n the refractive index of the fiber. In the instant case, for n = 1.5,

$$\ell = 2 \text{ cm}.$$

To compensate for this, the length difference $\Delta\ell_1$ between the longest delay line 23-1 and the shortest delay line 23-i is, accordingly, 2 cm. The differential lengths for the intermediate lines would be scaled in proportion to the wavelength of the several signal components.

FIG. 6 illustrates a multiplexer/demultiplexer that can be used to implement the invention. The device is of the type described by C. Dragone in a paper entitled "An NxN Optical Multiplexer Using a Planar Arrangement of Two Star Couplers," published September 1991 in IEEE Photonics Technology Letters, Vol. 3, No. 9. This arrangement includes a pair of star couplers 60 and 61 connected by a grating 62, comprising an array of delay lines. In operation, an input signal, including a plurality of wavelength components λ_1, λ_2 ... λ_i, is applied to star coupler 60. At the output of star coupler 61 the different wavelength components are separated and leave the coupler along its separate path for application to the differential delay lines 23 of the compensator.

FIG. 7 shows an alternate embodiment of a dispersion compensator in accordance with the invention using multiplexer/demultiplexers employing a reflective focusing diffraction grating of the type described by M. Born and E. Wolf in their book "Principles of Optics" published in 1959 by The Macmillan Company of New York. Also see the article entitled "Monolithic InP/InGaAs/InP grating spectrometer for the 1.48-1.56 µm wavelength range" published by J.B.D. Soole et al. in the 6 May 1991 issue of Applied Physics Letters, 56.

It is an advantage of the above-described devices that they are essentially lossless. Accordingly, the use of such devices to serve as the input demultiplexer and output multiplexer in a dispersion compensator in accordance with the present invention is without penalty.

In the embodiment of a dispersion compensator illustrated in FIG. 8, wavelength separation is achieved by the use of bandpass filters. In this embodiment the dispersion compensator comprises an input star coupler 81 and an output star coupler 82, connected by means of the differential delay lines 83. Be-

cause all the wavelength components are present at the outputs of coupler 81, each of the delay lines includes a bandpass filter 84-1, 84-2, ... 84-i, tuned to pass one of the wavelength components. As explained herein above, each delay line is adjusted to provide the delay appropriate to the wavelength passed by the filter in that line. While simpler to construct, the losses in such a device would be substantially higher than the losses using the multiplexer/demultiplexers illustrated in FIGS. 6 and 7.

In the discussion thus far, dispersion compensation of only one input signal has been considered. However, optical transmission systems usually carry a plurality of multiplexed channels. In such cases, the invention can be employed to simultaneously compensate all the channels by designing the compensator such that it has a free spectral range equal to the channel spacing, or a multiple thereof.

Claims

1. A dispersion compensator comprising:
   an input demultiplexer;
   an output multiplexer;
   and a plurality of different delay lines connecting the output ports of said demultiplexer to the input ports of said multiplexers.

2. A dispersion compensator comprising:
   input means for separating an input signal onto its wavelength components;
   means for delaying said wavelength components different lengths of time;
   and output means for recombining said delayed components in a common wavepath.

3. The compensator according to claim 2 wherein shorter wavelength components are delayed longer than longer wavelength components.

4. The compensator according to claim 2 wherein said input means includes:
   a star coupler having an input port and a plurality of output ports connected to an equal plurality of wavelength filters;
   and wherein:
   said output means comprises a star coupler having a plurality of input ports coupled to said delay means;
   and an output port coupled to said common wavepath.

FIG. 1
(PRIOR ART)

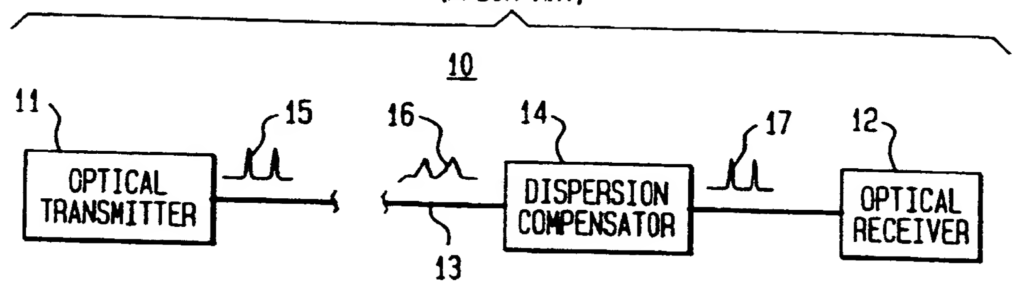


FIG. 2

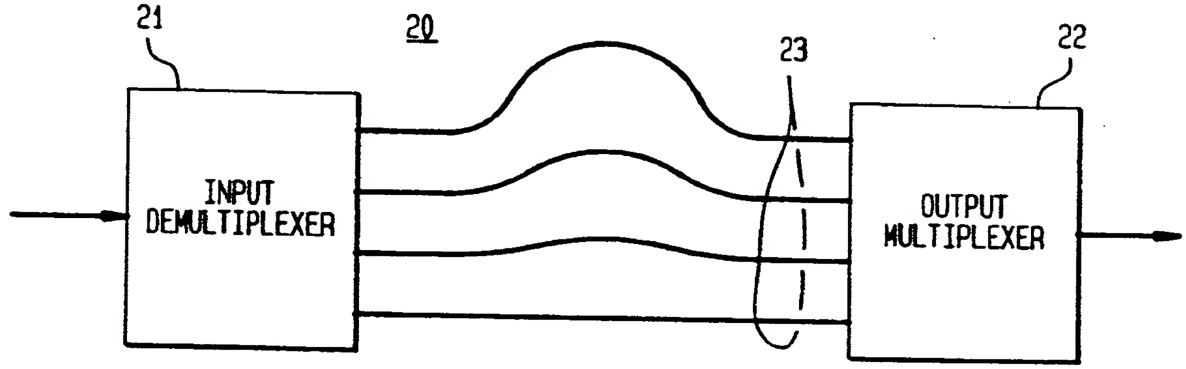


FIG. 3

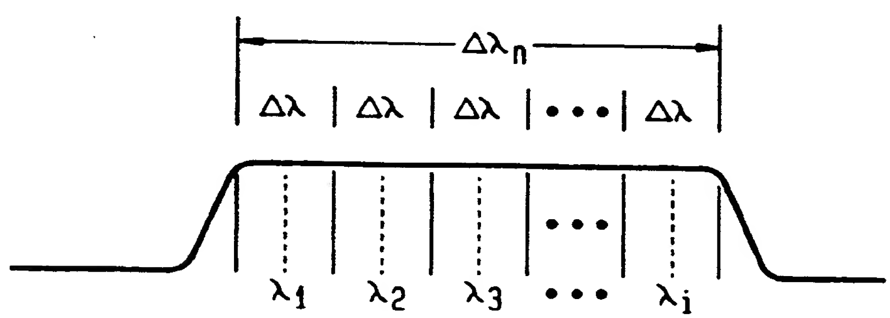


FIG. 4

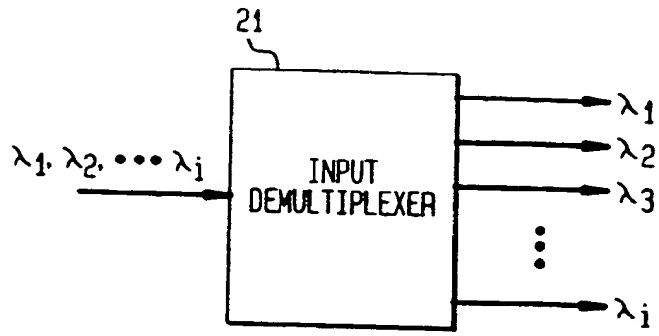


FIG. 5

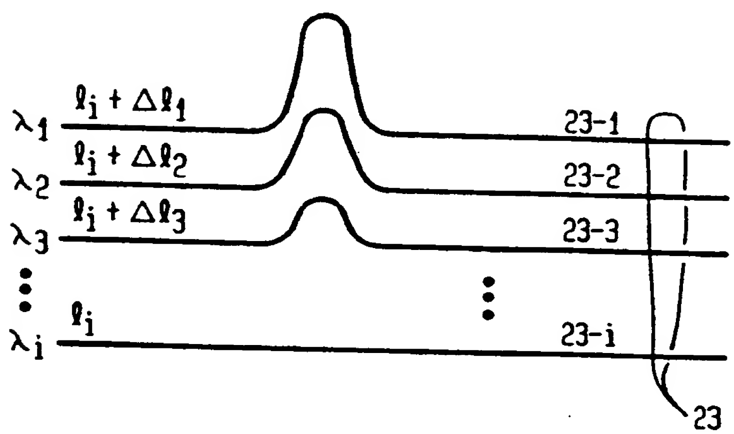


FIG. 6
(PRIOR ART)

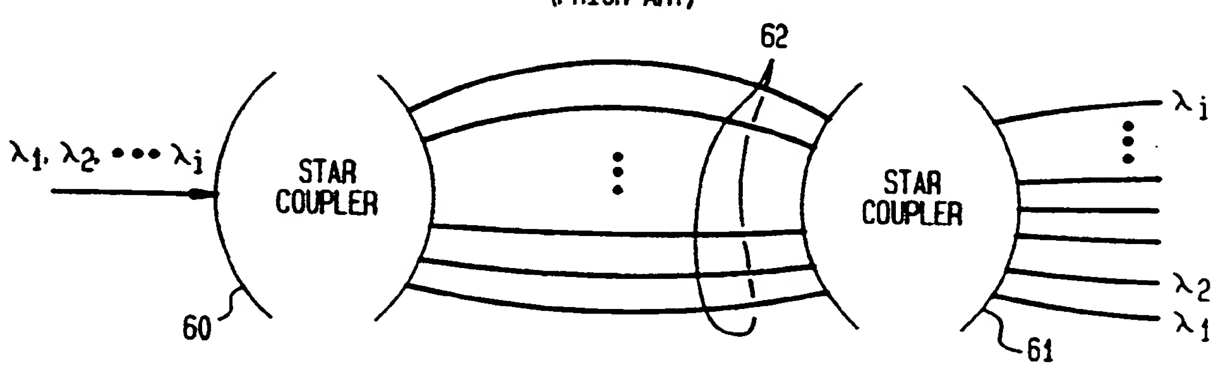


FIG. 7

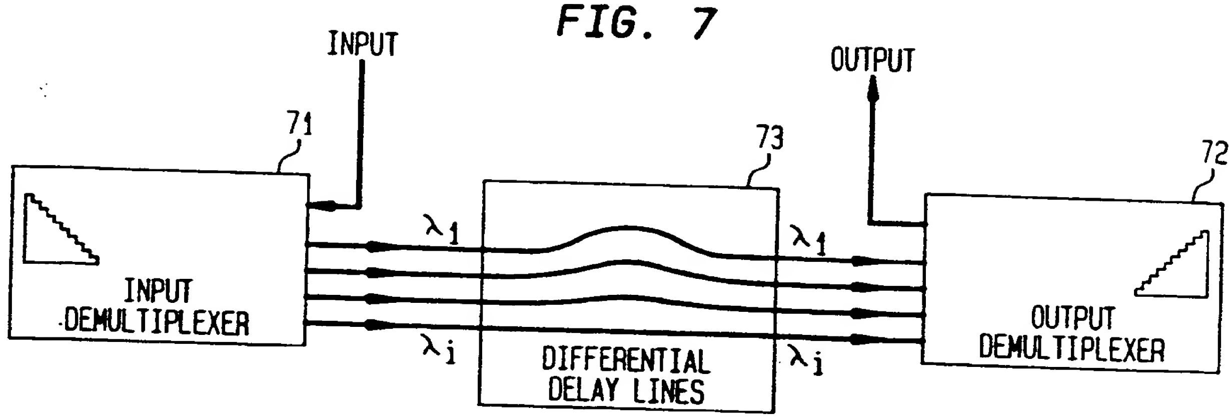
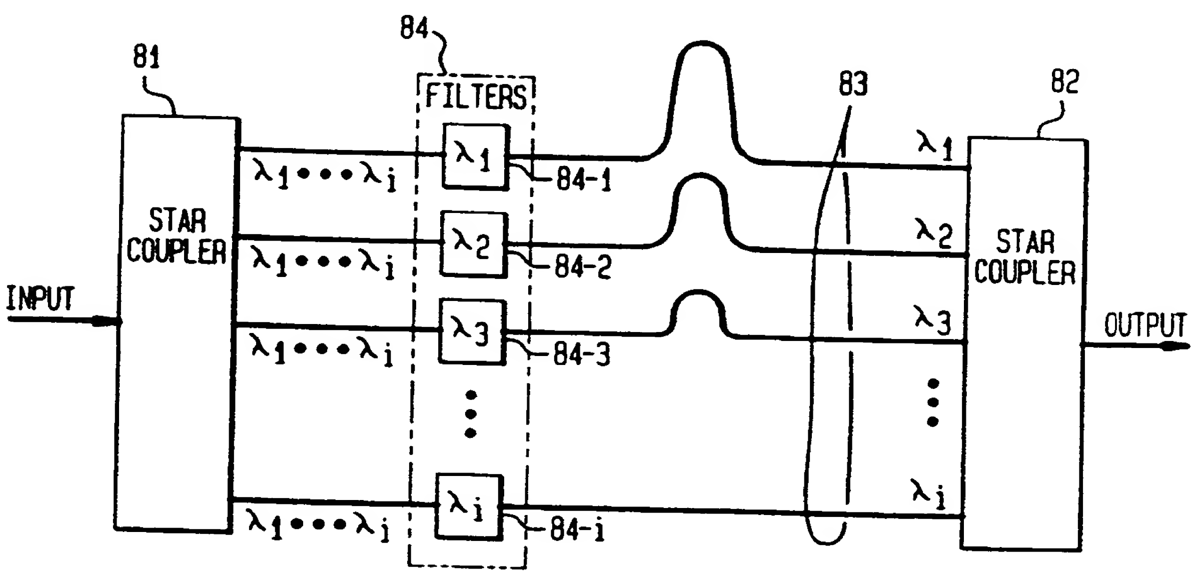

INPUT
OUTPUT
71
73
72
λ1
λi
λ1
λi
INPUT DEMULTIPLEXER
DIFFERENTIAL DELAY LINES
OUTPUT DEMULTIPLEXER

FIG. 8


84
81
FILTERS
83
82
λ1•••λi
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84-i
λ1
λ2
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λi
STAR COUPLER
OUTPUT

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 94 30 8073

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
X	PATENT ABSTRACTS OF JAPAN vol. 9, no. 169 (E-328) (1892) 13 July 1985 & JP-A-60 043 929 (NIPPON DENKI) * abstract *	1,2	G02B6/293 G02B6/28 H04B10/18
A	DE-C-31 44 723 (WANDEL & GOLTERMAN) * the whole document *	1-3	
A	IEEE PHOTONICS TECHNOLOGY LETTERS, vol.5, no.2, February 1993, NEW YORK US pages 194 - 197 C.D.POOLE ET.AL. 'Elliptical-core dual mode fiber dispersion compensator' * the whole document *	1	
			TECHNICAL FIELDS SEARCHED (Int.Cl.6)
			G02B

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	23 March 1995	Mathyssek, K

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

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FIG. 1
(PRIOR ART)

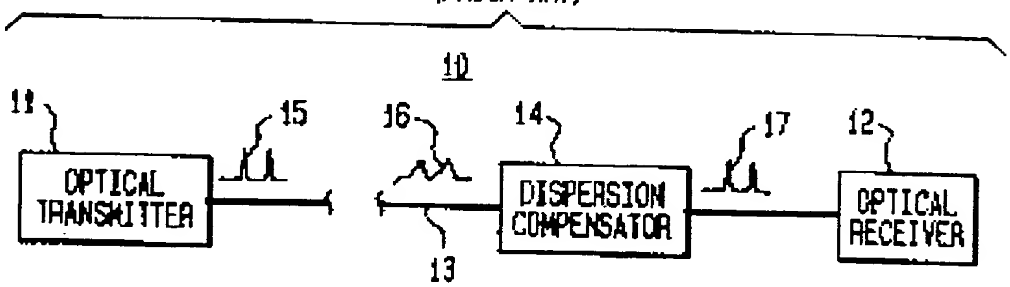


FIG. 2

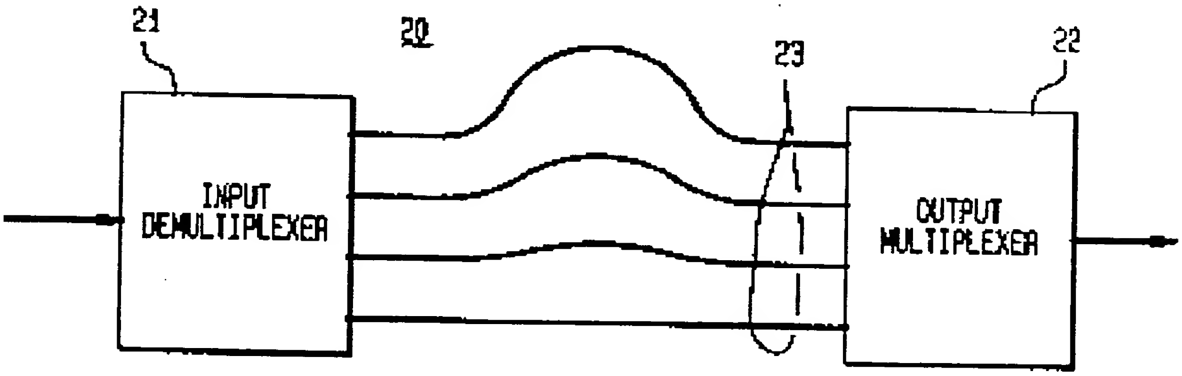


FIG. 3

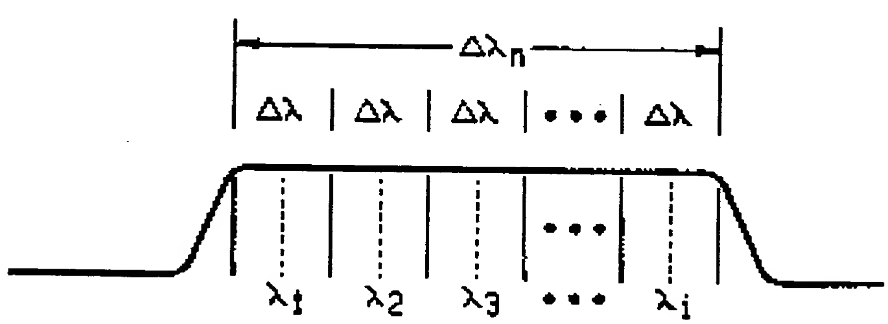


FIG. 4

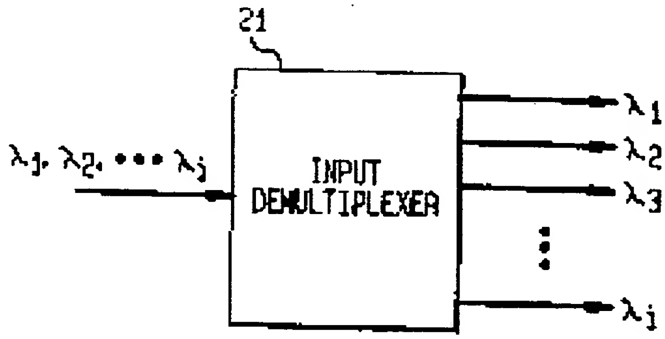


FIG. 5

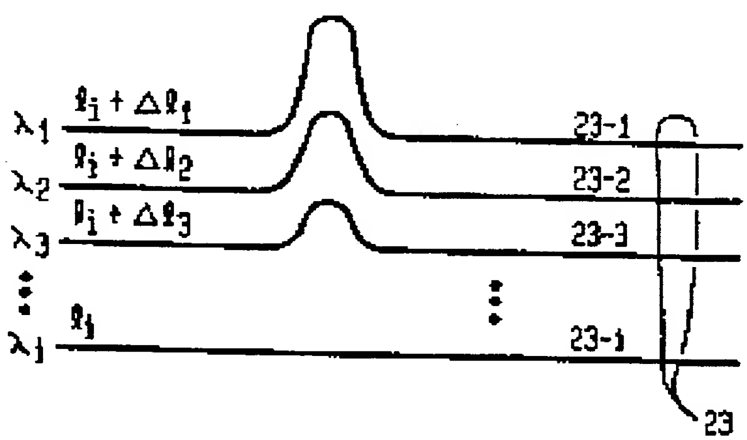


FIG. 6
[PRIOR ART]

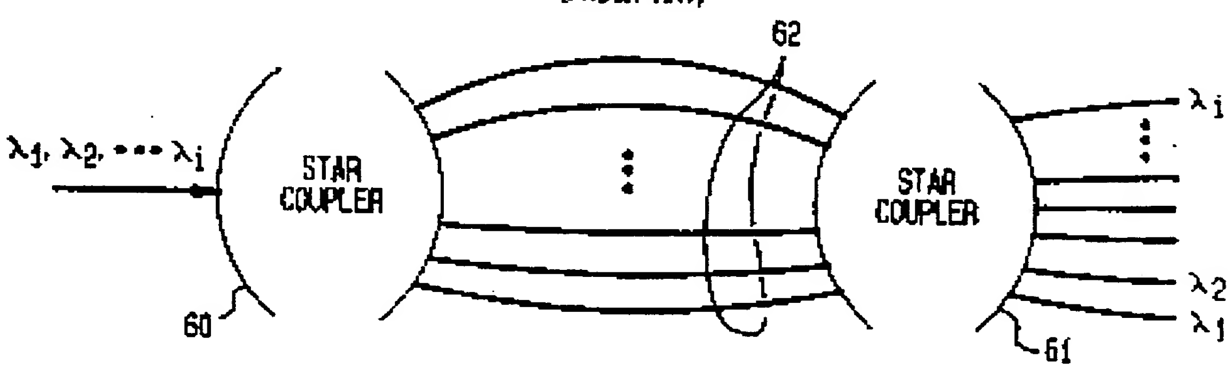
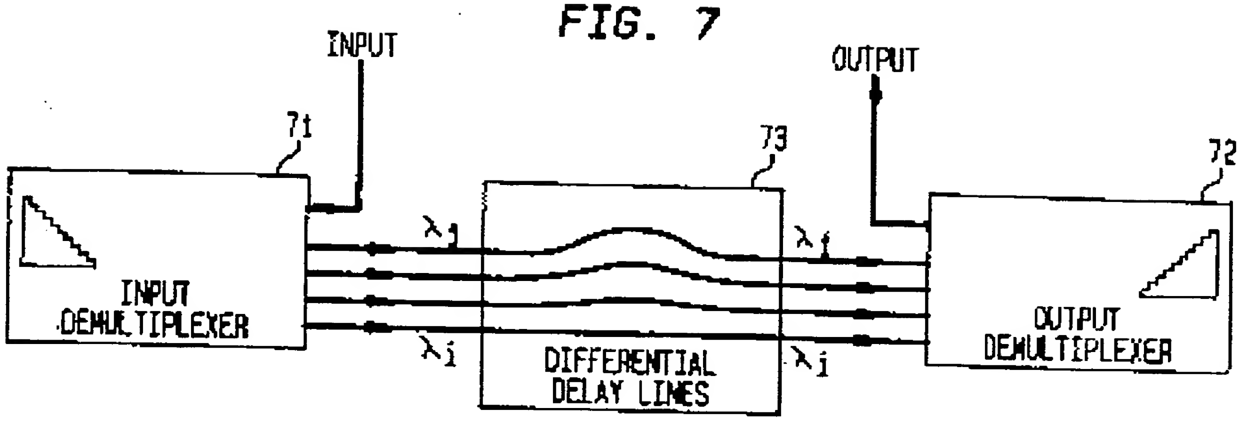


FIG. 7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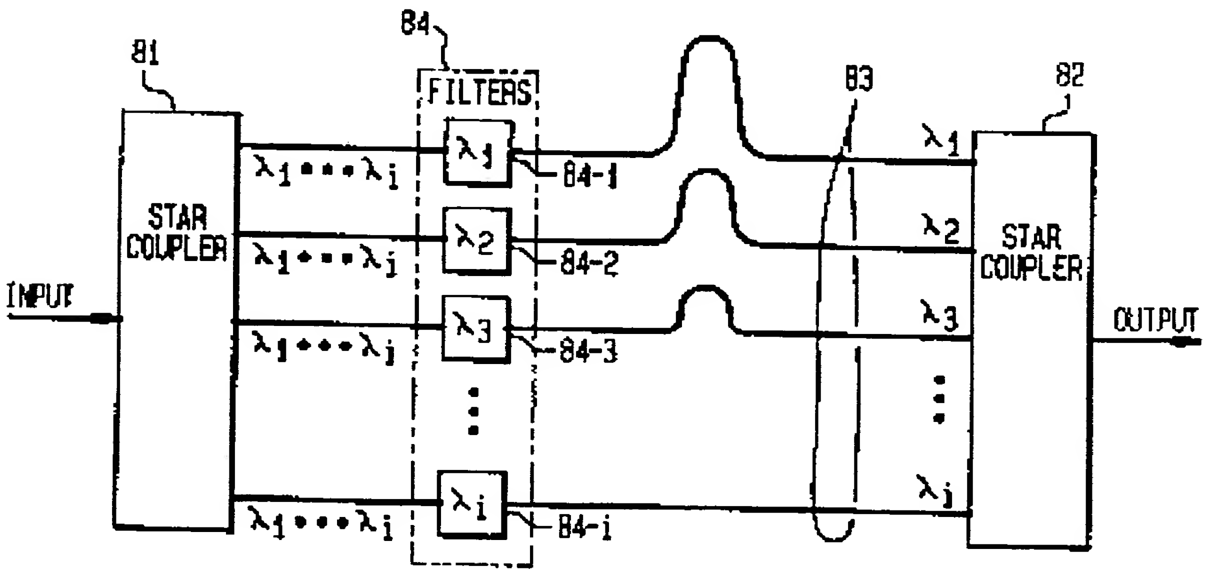
DIFFERENTIAL DELAY LINES
OUTPUT DEMULTIPLEXER

FIG. 8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84-3
84-i
STAR COUPLER
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